

# CHEMISTRY OF SELECTED HIGH-ELEVATION LAKES IN SEVEN NATIONAL PARKS IN THE WESTERN UNITED STATES

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**Abstract.** A chemical survey of 69 high-altitude lakes in seven national parks in the western United States was conducted during the fall of 1999; the lakes were previously sampled during the fall of 1985, as part of the Western Lake Survey. Lakes in parks in the Sierra/southern Cascades (Lassen Volcanic, Yosemite, Sequoia/Kings Canyon National Parks) and in the southern Rocky Mountains (Rocky Mountain National Park) were very dilute; median specific conductance ranged from 4.4 to 12.2  $\mu\text{S cm}^{-1}$  and median alkalinity concentrations ranged from 32.2 to 72.9  $\mu\text{eq L}^{-1}$ . Specific conductances and alkalinity concentrations were substantially higher in lakes in the central and northern Rocky Mountains parks (Grand Teton, Yellowstone, and Glacier National Parks), probably due to the prevalence of more reactive bedrock types. Regional patterns in lake concentrations of  $\text{NO}_3$  and  $\text{SO}_4$  were similar to regional patterns in  $\text{NO}_3$  and  $\text{SO}_4$  concentrations in precipitation, suggesting that the lakes are showing a response to atmospheric deposition. Concentrations of  $\text{NO}_3$  were particularly high in Rocky Mountain National Park, where some ecosystems appear to be undergoing nitrogen saturation.

**Keywords:** alpine, atmospheric deposition, high-elevation, lake chemistry, monitoring, nitrogen saturation, subalpine

## 1. Introduction

Lakes and streams in the mountains of the western United States are an important natural resource, providing water for human consumption, agriculture, and industry throughout the region. Large areas of the western mountains have thin, poorly-developed soils and slow-weathering granitic bedrock. Steep slopes and highly permeable soils are common. As a result, flow rates through soil typically are fast, especially during the snowmelt period, when large amounts of water are released from the snowpack in a short amount of time. If pollutants, such as sulfuric acid or nitrogen compounds, exist in the snowpack or in summer rains, there is minimal opportunity for neutralization or uptake because of limited buffering capacity and because of the short contact time between water and soils. These environmental factors tend to make high-elevation aquatic ecosystems in the western United States vulnerable to the effects of pollutants in atmospheric deposition.

In 1985, the U.S. Environmental Protection Agency and the U.S. Department



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of Agriculture, Forest Service, conducted a survey of water quality of lakes in mountainous areas of the western United States (Eilers *et al.*, 1987; Landers *et al.*, 1987). The purpose of the study, referred to as the 'Western Lake Survey', was to evaluate the current status of surface-water chemistry in areas of the western United States considered likely to be sensitive to the effects of acidic deposition. The Western Lake Survey (WLS) used a stratified random sampling of lakes; 719 lakes were sampled representing a target population of 10,393 of lakes. For the target population of lakes, the median specific conductance (SC) was  $16.5 \mu\text{S cm}^{-1}$ , and the median alkalinity was  $119 \mu\text{eq L}^{-1}$  (Eilers *et al.*, 1987; Landers *et al.*, 1987). These results confirmed the extremely dilute, and thus, sensitive character of lakes in the western United States.

Lakes in wilderness areas managed by the National Park Service and the Forest Service were found to be particularly sensitive, having a median alkalinity of  $91 \mu\text{eq L}^{-1}$  (Landers *et al.*, 1987). The greater sensitivity of lakes in wilderness areas compared to the larger group of WLS lakes reflects the high elevation and paucity of soil and vegetation in wilderness areas. Lakes in wilderness areas receive special protection under the Wilderness Act and Clean Air Act, which specify that no degradation of aquatic resources may result from new sources of atmospheric deposition. Many cities near Wilderness Areas in the west are experiencing high rates of growth, leading to increased automobile and industrial emissions and to construction of new electric power-generating facilities. Deposition of nitrogen compounds, largely derived from automobiles, gas-fired power plants, and agriculture, has increased in many areas of the western United States since the mid-1980's (Lynch *et al.*, 1996; Clow *et al.*, in review). High-elevation ecosystems in Rocky Mountain National Park and elsewhere in the Colorado Front Range exhibit symptoms of nitrogen saturation, as indicated by elevated concentrations of  $\text{NO}_3$  in surface water throughout the year (Williams *et al.*, 1996; Campbell *et al.*, 2000).

The effects of air pollution on aquatic resources in national parks is of special concern for resource managers, who are required by federal law to protect 'Air Quality Related Issues' such as visibility, water quality, clean air, and biological resources in the parks. These laws also specify that no degradation of water quality may occur as a result of air pollution in the parks. There has been no systematic assessment of water quality in the parks since the 1985 Western Lake Survey. A new assessment of the current status of water quality in national parks in the western United States is urgently needed by resource managers tasked with protecting aquatic resources in the parks.

The U.S. Geological Survey, in cooperation with the National Park Service, conducted a synoptic survey of high-elevation lake chemistry in wilderness areas of seven national parks in the western United States during fall 1999. Of the 72 lakes that were sampled in the western parks during the Western Lake Survey in 1985, 69 were resampled in 1999. The objective of the study was to (1) document the current chemical status of high-elevation lakes in national parks in the western United States that were previously sampled in the Western Lake Survey,



Figure 1. Locations of national parks in the western United States that were part of 1999 lake sampling study.

(2) evaluate differences in water chemistry between the 1985 and 1999 surveys, and (3) identify relations between water quality and basin characteristics. The focus of this paper is on objective 1. Objective 2 is addressed in Clow *et al.* (in review).

## 2. Basin Characteristics

The locations of the parks sampled in this study are shown in Figure 1. Lassen Volcanic National Park is in the southern part of the Cascade mountains, and Yosemite and Sequoia/Kings Canyon National Parks are in the Sierra Nevada; these parks are referred to in the text as the 'Sierra/south Cascade Parks'. Glacier, Yellowstone, Grand Teton, and Rocky Mountain National Parks are in the Rocky Mountains.

All of the parks are in recently-glaciated, mountainous terrain (Madole, 1976; Fullerton, 1986; Richmond and Fullerton, 1986). Most of the lakes sampled in this study were in the alpine/subalpine zone, where soils are young, thin, and poorly developed. Soils generally are cryic (cold), and show little horizon development, particularly in the alpine zone. Vegetation is scarce in the alpine zone, which grades into open subalpine forest at lower elevations (Rundel *et al.*, 1977; Arthur, 1992). Dominant bedrock types in the parks include granite/granodiorite in Yosemite and Sequoia/Kings Canyon National Parks (Ross, 1958; Bateman, 1992), dacite in Lassen Volcanic National Park (Diller, 1894), basalt, tuff, and rhyolite in Yellowstone National Park (U.S. Geological Survey, 1972), granitic rocks in Rocky Mountain and Grand Teton National Parks (Braddock and Cole, 1990; Love *et al.*, 1992), and sedimentary rocks including argillite, siltite, and limestone in Glacier National Park (Whipple, 1992). A summary of basin characteristics is given in Table I; additional details are in Melack and Stoddard (1991) and Turk and Spahr (1991) and references contained therein. Photographs of most of the sampled lakes are available at <http://co.water.usgs.gov/projects/CO335/CO335.html>.

Most precipitation in the alpine/subalpine zone falls as snow, which commonly accumulates in a seasonal snowpack from November through April. Snowmelt, which usually peaks in May and June, is the dominant surface-water event of the year, generally accounting for >70% of annual streamflow in the Rocky Mountains and >90% of annual streamflow in the Sierra Nevada (Lawrence, 1987). Most of the lakes are small and shallow; approximately 75% of the lakes have areas  $\leq 9$  ha and depths  $\leq 16$  m (Table I). Basin area to lake area ratios generally are large; more than 75% of the ratios are  $\geq 15$ . Annual precipitation amounts generally are sufficient to flush most of the lakes completely several times during snowmelt (Turk and Spahr, 1991). Summer rain is infrequent in the Sierra Nevada, but is common in the Rocky Mountains due to convective thunderstorms.

Land use in the parks is restricted to recreation; logging, mining, and off-road vehicle use are not allowed. All of the sampled lakes are in remote areas of the parks managed as wilderness areas, far from roads or other developments, and influences from human activities in the study basins are likely to be negligible (Melack and Stoddard, 1991).

### 3. Methods

Sample collection, processing, and analytical methods were similar to those used in the 1985 Western Lake Survey (Kerfoot and Faber, 1987). Samples were collected during late fall, after most lakes had turned over. Samples were collected at the outflows of all the lakes using strict, low-level trace metal clean techniques (Wilde *et al.*, 1998). In the Western Lake Survey, samples were collected from the epilimnion at the deepest location of the lake, in most cases using a pontoon-equipped helicopter as a platform. In the present study, lake access was by foot,

TABLE I  
Lake and lake basin characteristics

		Elevation (m)	Lake area (ha)	Ratio of basin area: lake area	Lake depth (m)
Glacier					
n = 4	Mean	1728	68.7	25	20.3
	1st quartile	1394	4.2	14	16.9
	Median	1743	54.6	24	18.5
	3rd quartile	2077	119.1	36	21.8
Yellowstone					
n = 6	Mean	2346	15.7	32	8.5
	1st quartile	2221	6.3	8	6.3
	Median	2340	13.4	16	6.7
	3rd quartile	2484	19.5	32	8.5
Grand Teton					
n = 1		2598	1.4	263	4.9
Rocky Mountain					
n = 22	Mean	3281	4.9	59	11.3
	1st quartile	3143	2.3	18	4.0
	Median	3312	3.0	36	8.3
	3rd quartile	3373	5.9	75	16.2
Lassen Volcanic					
n = 7	Mean	2158	4.3	21	7.9
	1st quartile	2043	2.5	11	5.2
	Median	2098	3.6	15	6.3
	3rd quartile	2220	6.1	21	6.6
Yosemite					
n = 9	Mean	2822	14.8	45	8.9
	1st quartile	2720	5.2	18	6.4
	Median	2940	9.1	19	7.3
	3rd quartile	3111	26.0	35	12.2
Sequoia/Kings Canyon					
n = 20	Mean	3326	4.7	34	10.7
	1st quartile	3240	2.5	15	4.8
	Median	3318	3.6	22	6.9
	3rd quartile	3525	6.0	46	16.1

Data source: <http://www.epa.gov/emap/html/otherdata/napap/>.

usually without watercraft. It was hypothesized that outflow chemistry would not be significantly different from epilimnion chemistry because most of the lakes sampled are small, shallow, and frequently mixed by wind and/or streamflow. To test for possible sample location bias, outflow and epilimnion samples (mid-lake, using a small raft) were collected at 14% of the lakes.

Filtered and unfiltered aliquots of outflow and epilimnion water were collected using a peristaltic pump. Filtered aliquots were obtained by passing sample water through 0.45  $\mu\text{m}$  pore size polysulfonate membrane filters, which were in cartridges attached to the outlet end of the tubing. Filters were rinsed with 500 mL of 18 M-ohm deionized, distilled water in the field immediately prior to use. Sample water was pumped directly from the outflow stream or from the lake directly into precleaned sample bottles, which were triple-rinsed with sample water. Total mercury (Hg) and methylmercury (MeHg) were collected in rigorously cleaned Teflon bottles, and were acidified in a portable glove box within 8 hr of collection using high-purity hydrochloric acid (Krabbenhoft *et al.*, this issue). Samples were hermetically sealed and kept cool and in the dark during transport from the field and shipment to the analytical laboratory.

Alkalinity, pH, and specific conductance (SC) were measured in the laboratory on unfiltered aliquots within 1 week of collection. Alkalinity was measured by Gran titration (Gran, 1952), and pH was measured using an electrode designed for low-ionic strength water. Calcium (Ca), magnesium (Mg), and silica ( $\text{H}_4\text{SiO}_4$ ) were determined by inductively coupled plasma spectroscopy on filtered, acidified samples within 2 months of collection. Sodium (Na), potassium (K), ammonium ( $\text{NH}_4$ ), sulfate ( $\text{SO}_4$ ), nitrate ( $\text{NO}_3$ ), and chloride (Cl) were measured by ion chromatography on filtered, unacidified aliquots within 1 month of collection. Dissolved organic carbon (DOC) was measured by UV-promoted persulfate oxidation and infrared spectrometry, and ultra-violet absorbance (UVA) was measured at 254 nm. DOC and UVA were measured within 1 month of collection. Detection limits were less than 1  $\mu\text{mol L}^{-1}$  for all dissolved constituents, except DOC, which had a detection limit of 0.3  $\text{mg L}^{-1}$ . Analytical methods for Hg and MeHg are presented in Krabbenhoft *et al.* (this issue).

Quality-assurance procedures included collection and analyses of field blanks and field splits, each of which comprised 10% of the total sample load. Solute concentrations in all of the field blanks were less than the detection limit for all constituents. Median differences of field splits were  $\leq 1 \mu\text{mol L}^{-1}$ , except for alkalinity and Ca, for which median differences were  $\leq 2 \mu\text{mol L}^{-1}$ . Accuracy of analyses was evaluated using certified high-purity standards traceable to the National Institute of Standards, standard reference samples obtained from the U.S. Geological Survey, Branch of Quality Systems (Ludtke and Woodworth, 1997) and participation in blind-audit performance tests conducted by the U.S. Geological Survey and by the National Laboratory for Environmental Testing, National Water Research Institute, Environment Canada (Blum and Alkema, 2000). Results of these tests indicated analyses were accurate to within 1% for most constituents and

within 6% for all of them. Analytical results were checked by comparing measured and predicted SC, and by ionic charge balance, ie., the difference between total cation and total anion concentrations. A more detailed analysis of QA results from this study and from the WLS is provided in Clow *et al.* (in review).

## 4. Results

### 4.1. COMPARISON OF LAKE-OUTFLOW AND EPILIMNION SAMPLES

Paired *t*-tests indicated no significant differences in temperature or chemistry between outflow and epilimnion samples at  $p = 0.05$ , and median differences were  $\leq 1 \mu\text{mol L}^{-1}$  for all solutes. Temperature profiles conducted at lakes where epilimnion samples were collected indicated that the lakes were isothermal. These results indicate that outflow water was comparable to epilimnion water and could be used as a surrogate for epilimnion lake chemistry.

Concentration data for all lake and outflow samples are available at <http://co.water.usgs.gov/projects/CO335/CO335.html>.

### 4.2. CONCENTRATIONS IN LAKE-OUTFLOW SAMPLES

Lakes in Lassen Volcanic, Yosemite, Sequoia/Kings Canyon, and Rocky Mountain National Park were very dilute, with median SC ranging from 4.4 to 12.2  $\mu\text{S cm}^{-1}$  (Table II). Specific conductance in the parks in the northern and central Rocky Mountains (Glacier, Yellowstone, and Grand Teton National Parks) were substantially higher, ranging from 30.9 to 127.1  $\mu\text{S cm}^{-1}$  (Table II). The lake that was sampled in Grand Teton National Park is at relatively low elevation, and probably is not representative of surface-water chemistry of most lakes in the park, which generally are at higher elevation and likely to be substantially more dilute.

Median pH ranged from 6.6 to 6.9 in all parks except those in the northern Rockies, where median pH ranged from 7.4 to 7.8 (Table II). Only one lake was acidic – Fern Lake in Yellowstone National Park. Fern Lake and Nymph Lake, also in Yellowstone National Park, appear to be affected by natural hydrothermal solutions, as indicated by anomalously high concentrations of base cations, Cl,  $\text{SO}_4$ , and Hg (Table II).

Concentrations of  $\text{NH}_4$  commonly were below the detection limit, as expected for alpine/subalpine ecosystems during the growing season (Table II). Concentrations of  $\text{NO}_3$  were quite low in lakes in the Sierra/southern Cascade parks (Figure 2), where median values were less than the detection limit. In the parks in the Rockies, median  $\text{NO}_3$  concentrations ranged from 0.5 to 1.9  $\mu\text{eq L}^{-1}$ , and in many lakes  $\text{NO}_3$  concentrations exceeded 10  $\mu\text{eq L}^{-1}$ , especially in Rocky Mountain National Park. A few lakes in Yosemite and Sequoia/Kings Canyon National Park had  $\text{NO}_3$  concentrations  $>6 \mu\text{eq L}^{-1}$ , mostly in remote, alpine areas with abundant exposed bedrock and talus. Median  $\text{SO}_4$  concentrations in the Sierra/south Cascade

TABLE II  
Summary statistics for lakes sampled in national parks in western United States during fall, 1999

	Temp.	SC	pH	Alkalinity	Ca	Mg	Na	K	NH <sub>4</sub>	H <sub>4</sub> SiO <sub>4</sub>	Cl	SO <sub>4</sub>	NO <sub>3</sub>	DOC	UVA	Total Hg	MeHg
Glacier (n = 4)																	
Mean	13	44.4	7.4	457.2	307.6	157.5	10.4	3.0	≤0.5	20.3	1.8	21.8	2.0	0.7	0.01	0.60	0.010
Minimum	6	6.1	6.7	39.1	26.4	20.5	4.2	2.2	≤0.5	12.4	1.0	4.3	≤0.3	0.4	0.01	0.46	0.006
Median	13	30.9	7.4	31.5	239.3	129.6	10.5	3.0	≤0.5	13.0	1.7	17.2	1.7	0.7	0.02	0.62	0.010
Maximum	18	109.7	8.1	1154.7	725.5	350.5	16.6	3.7	1.1	42.7	2.8	48.6	4.6	0.9	0.02	0.69	0.012
Yellowstone (n = 6)																	
Mean	9	201.3	7.2	685.4	453.2	135.6	301.4	203.8	0.7	777.8	403.6	646.9	1.4	6.3	0.10	41.94	0.228
Minimum	5	21.0	4.3	-38.8	99.8	26.3	11.7	4.1	≤0.5	2.5	3.3	4.1	≤0.3	2.1	0.02	0.77	0.033
Median	9	127.1	7.8	533.7	319.8	74.0	110.3	47.5	≤0.5	627.9	16.8	30.3	0.5	4.9	0.08	2.17	0.073
Maximum	17	711.0	8.4	1621.1	1196.6	428.7	925.6	908.6	2.4	2222.1	1938.6	2937.3	5.1	11.7	0.25	231.54	0.734
Grand Teton (n = 1)																	
	6	39.3	7.5	326.7	225.0	69.9	50.9	30.6	≤0.5	105.3	4.8	33.1	3.5	1.0	0.03	0.57	0.042
Rocky Mountain (WLS only) (n = 22)																	
Mean	8	12.2	6.9	76.3	67.3	16.9	25.9	3.6	≤0.5	36.4	2.2	25.7	4.3	1.6	0.04	1.03	0.040
Minimum	4	6.3	6.3	14.7	28.4	8.2	7.9	2.0	≤0.5	8.3	1.3	12.8	≤0.3	≤0.3	0.01	0.44	0.001
Median	8	12.2	6.8	14.7	62.3	15.6	10.5	3.1	≤0.5	30.3	1.9	21.9	1.9	1.3	0.02	0.96	0.031
Maximum	11	23.9	7.2	175.1	140.2	46.9	97.3	8.4	3.9	152.6	6.9	65.9	15.4	7.0	0.17	2.02	0.214

Temperature (Temp.) is in °C; DOC is in mg L<sup>-1</sup>, specific conductance (SC) is in μS cm<sup>-1</sup>; H<sub>4</sub>SiO<sub>4</sub> is in μmol L<sup>-1</sup>; total Hg and MeHg are in ng L<sup>-1</sup>; all other units except pH are μeq L<sup>-1</sup>.

DOC refers to dissolved organic carbon. UVA refers to ultra-violet absorbance. MeHg refers to methylmercury.

Concentration data for individual samples is available at <http://co.water.usgs.gov/projects/CO335/CO335.html/>.



TABLE II  
(continued)

	Temp.	SC	pH	Alkalinity	Ca	Mg	Na	K	NH <sub>4</sub>	H <sub>4</sub> SiO <sub>4</sub>	Cl	SO <sub>4</sub>	NO <sub>3</sub>	DOC	UVA	Total Hg	MeHg
Lassen Volcanic (n = 7)																	
Mean	16	7.0	6.7	61.7	26.2	20.4	15.1	4.4	0.6	37.3	2.5	4.0	≤0.3	1.3	0.02	0.88	0.034
Minimum	14	3.1	6.3	13.8	5.9	5.7	6.7	1.5	≤0.5	5.3	1.7	0.6	≤0.3	≤0.3	0.01	0.56	0.013
Median	16	4.4	6.7	38.6	10.4	15.6	8.4	4.4	≤0.5	9.9	2.6	2.3	≤0.3	≤1.5	0.02	0.90	0.016
Maximum	19	17.0	7.2	165.4	82.8	56.7	36.4	8.9	1.8	104.8	2.9	16.4	≤0.3	2.3	0.04	1.25	0.081
Yosemite (n = 9)																	
Mean	12	6.2	6.6	41.7	29.1	4.8	17.6	3.7	≤0.5	27.8	1.7	5.8	0.7	0.9	0.02	0.75	0.026
Minimum	8	2.9	6.2	13.7	6.4	1.6	6.3	2.2	≤0.5	8.3	0.7	1.7	≤0.3	≤0.3	0.01	0.00	0.000
Median	12	5.6	6.6	32.2	26.9	4.1	16.4	2.8	≤0.5	24.4	1.7	3.8	≤0.3	0.8	0.01	0.65	0.004
Maximum	17	10.3	6.9	75.3	61.8	9.8	27.5	8.4	4.0	68.9	2.5	13.2	6.53	1.9	0.03	1.15	0.086
Sequoia/Kings Canyon (n = 20)																	
Mean	13	9.0	6.8	63.5	57.8	5.5	19.2	3.3	0.6	38.4	1.9	9.1	0.9	1.6	0.02	0.86	0.037
Minimum	7	3.1	6.0	7.2	11.4	1.6	4.3	1.8	≤0.5	7.1	0.9	1.2	≤0.3	≤0.3	0.00	0.27	0.002
Median	13	8.8	6.9	59.0	55.4	3.7	19.4	3.0	≤0.5	27.9	1.4	6.7	≤0.3	1.2	0.02	0.73	0.016
Maximum	21	21.0	7.3	151.9	177.1	13.9	48.2	6.4	4.2	82.2	6.2	41.1	8.3	8.5	0.18	2.84	0.191
Total (n = 7)																	
Mean	11	28.7	6.9	146.5	105.2	31.6	45.2	21.3	0.5	100.5	37.0	70.0	2.0	1.8	0.03	4.45	0.052
Minimum	4	2.9	4.3	–	5.9	1.6	4.2	1.5	≤0.5	2.5	0.7	0.6	≤0.3	≤0.3	0.00	0.00	0.000
Median	11	10.1	6.8	61.8	57.8	12.3	18.8	3.3	≤0.5	28.3	2.0	10.1	≤0.3	1.2	0.02	0.86	0.030
Maximum	21	711.0	8.4	1621.1	1196.6	428.7	925.6	908.6	4.2	2222.1	1938.6	2937.3	15.4	11.7	0.25	231.54	0.734

Temperature (Temp.) is in °C; DOC is in mg L<sup>-1</sup>, specific conductance (SC) is in  $\mu\text{S cm}^{-1}$ ; H<sub>4</sub>SiO<sub>4</sub> is in  $\mu\text{mol L}^{-1}$ ; total Hg and MeHg are in ng L<sup>-1</sup>; all other units except pH are  $\mu\text{eq L}^{-1}$ .

DOC refers to dissolved organic carbon. UVA refers to ultra-violet absorbance. MeHg refers to methylmercury. Concentration data for individual samples is available at <http://co.water.usgs.gov/projects/CO335/CO335.html/>.

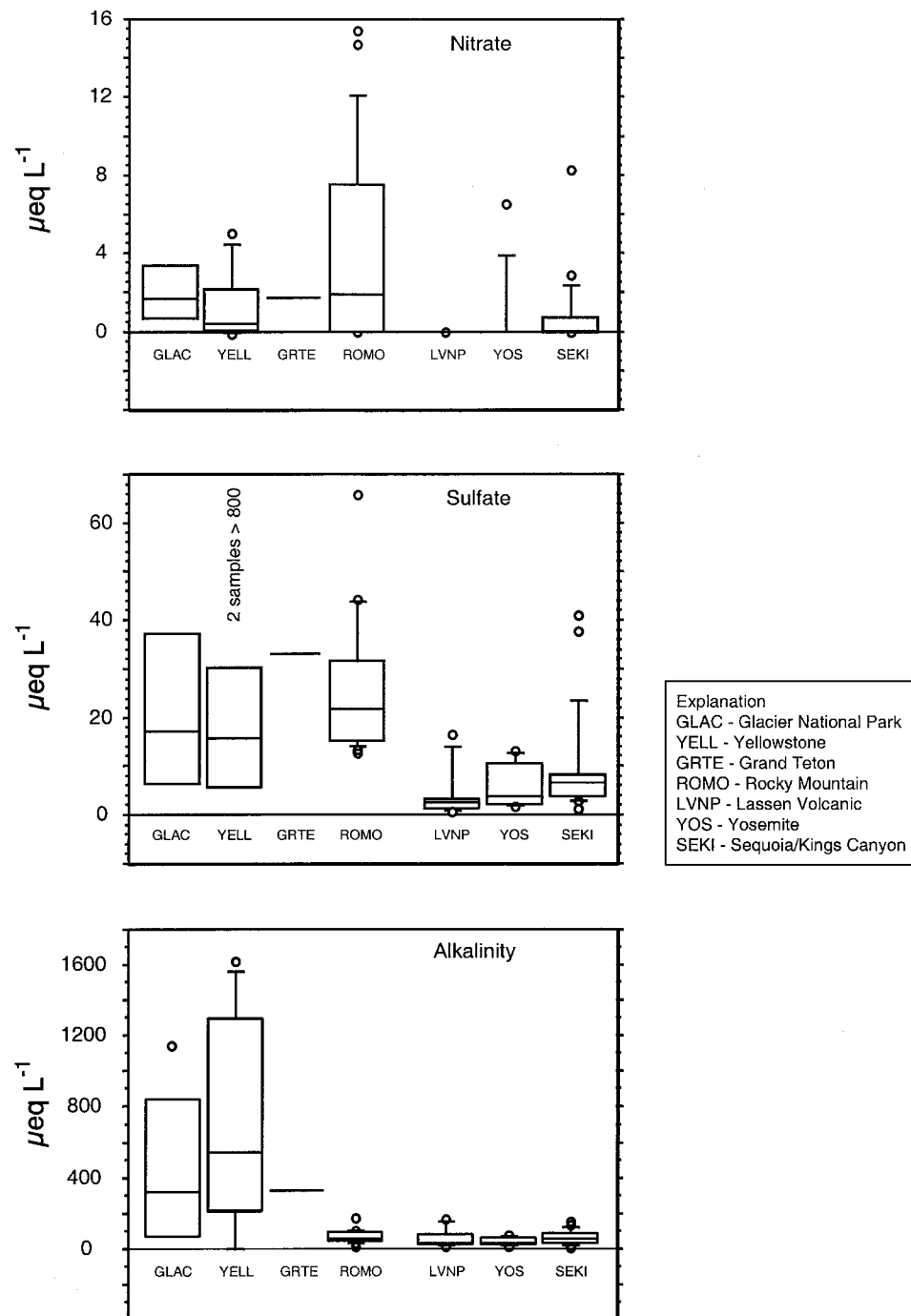


Figure 2. Box plots showing major ion concentrations in lakes in national parks in the western United States. Lines show medians, boxes show interquartile range, whiskers show 10th and 90th percentiles, and circles show outliers.

parks were low, ranging from 2.3 to 6.7  $\mu\text{eq L}^{-1}$  (Table II, Figure 2). Median  $\text{SO}_4$  concentrations were substantially higher in the parks in the Rocky Mountains, ranging from 17.2 to 33.1  $\mu\text{eq L}^{-1}$ .

Alkalinity concentrations were very low in Lassen Volcanic and Yosemite National Parks, where median alkalinity values were 38.6 and 32.2  $\mu\text{eq L}^{-1}$  (Table II, Figure 2). Median alkalinities were somewhat higher in Sequoia/Kings Canyon (59  $\mu\text{eq L}^{-1}$ ) and in Rocky Mountain National Park (72.9  $\mu\text{eq L}^{-1}$ ). In the parks in the northern and central Rockies, median alkalinities ranged from 317.5 to 533.7  $\mu\text{eq L}^{-1}$  (Table II, Figure 2).

Calcium concentrations were very low in Lassen Volcanic and Yosemite National Parks, with median values of 10.4 and 26.9  $\mu\text{eq L}^{-1}$ , respectively (Table II). Concentrations of Ca were somewhat higher in Sequoia/Kings Canyon and Rocky Mountain National Parks, where median concentrations were 55.4 and 62.3  $\mu\text{eq L}^{-1}$ . In the parks in the northern and central Rockies, Ca concentrations were much higher (medians  $\geq 225 \mu\text{eq L}^{-1}$ ). Spatial patterns in concentrations of Mg, Na, and K concentrations generally were similar to those of Ca, with low concentrations in the California parks and in Rocky Mountain National Park, and much higher concentrations in parks in the northern and central Rocky Mountains (Table II).

Concentrations of Cl generally were quite low and most were similar to concentrations found in local precipitation, except in Yellowstone National Park, where high Cl concentrations in some lakes indicate inputs of hydrothermal solutions (Table II). Approximately 80% of lakes had Cl concentrations  $< 3 \mu\text{eq L}^{-1}$ , indicating that evapotranspiration did not greatly affect the chemistry of most lakes.

Concentrations of Hg and MeHg were low ( $\leq 2.84 \text{ ng L}^{-1}$  and  $\leq 0.214 \text{ ng L}^{-1}$ , respectively), except at two lakes in Yellowstone National Park (Nymph Lake and Fern Lake), which probably were influenced by hydrothermal solutions. Detailed results and interpretations of Hg and MeHg data are presented in Krabbenhoft *et al.*, (this issue).

## 5. Geographic Patterns in Concentrations of Nitrate, Sulfate, and Weathering Products

### 5.1. NITRATE

Geographic patterns in lake nitrate concentrations may be influenced by regional differences in atmospheric deposition, climate, and basin physical characteristics. Atmospheric deposition of inorganic N-compounds ( $\text{NH}_4$  and  $\text{NO}_3$ ) is an important source of nitrogen in alpine/subalpine ecosystems in the western United States, where local nutrient sources typically are minor. Most atmospherically-deposited  $\text{NH}_4$  is quickly assimilated by biota after it is deposited (Stoddard, 1994). Some may subsequently be released to surface water as  $\text{NO}_3$  through nitrification. Although generally less important than inorganic N, organic forms of N can be a significant fraction of total N deposition (Neff *et al.*, in press).

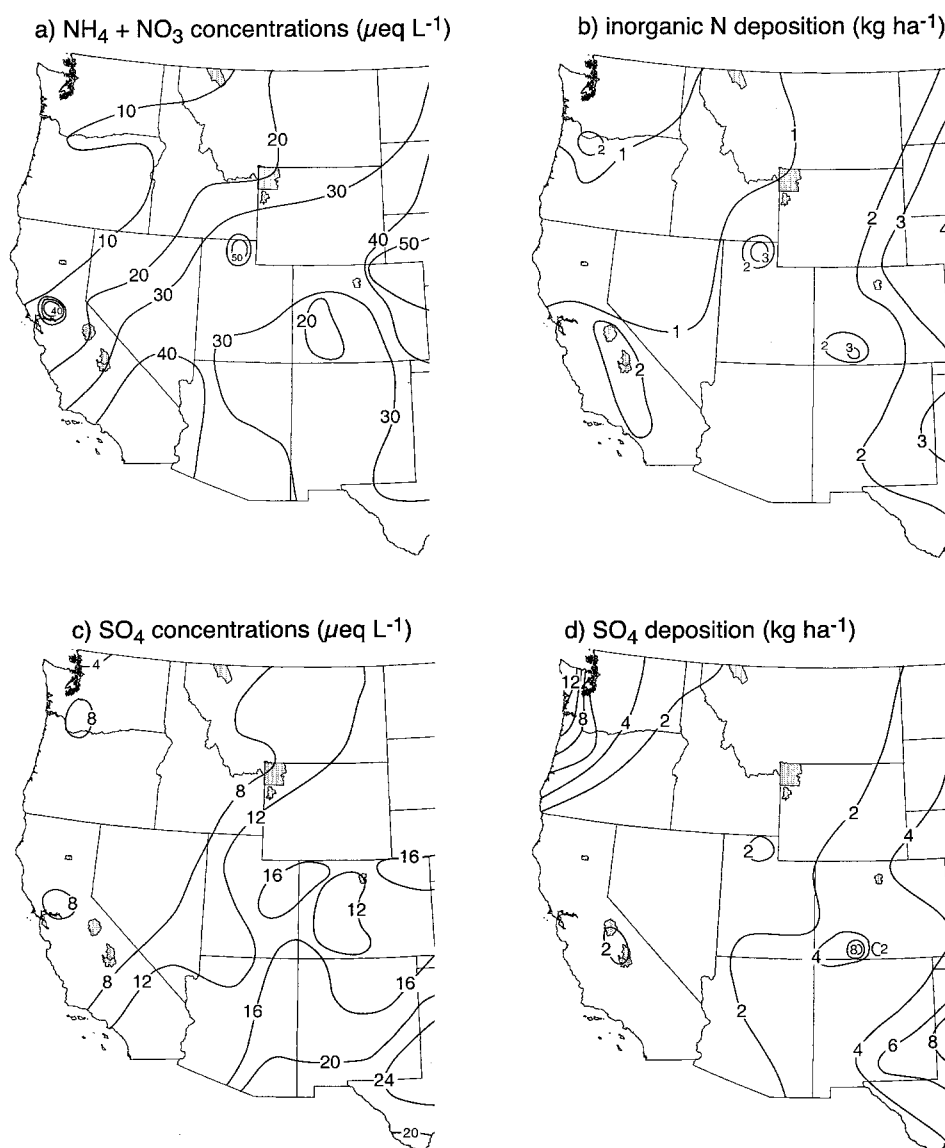


Figure 3. Isopleth maps showing (a)  $\text{NH}_4 + \text{NO}_3$  concentrations, (b) inorganic N deposition, (c)  $\text{SO}_4$  concentrations, and (d)  $\text{SO}_4$  deposition in precipitation in the western United States during water year 1999 (October 1998 through September 1999) (data source: National Atmospheric Deposition Program (NRSP-3)/National Trends Network, Illinois State Water Survey, Urbana, 2000, <http://nadp.sws.uiuc.edu/>).

A comparison of geographic patterns  $\text{NO}_3$  concentrations in lakes and inorganic N in precipitation provides insight into possible relations between them. Annual volume-weighted mean inorganic N concentrations ( $\text{NH}_4 + \text{NO}_3$ ) in precipitation in water year 1999 (October, 1998 through September, 1999) were calculated for NADP/NTN sites in the western United States, and isopleth maps were created by interpolation between sites (Figure 3a). Regional patterns in lake  $\text{NO}_3$  concentrations measured in this study and in  $\text{NH}_4 + \text{NO}_3$  concentrations measured in precipitation were similar. Inorganic N concentrations in precipitation and in lakes (Table II, Figure 3a) generally increased from north to south and west to east. This similarity in regional patterns of inorganic N concentrations suggests that the lakes are showing a response to atmospheric deposition of nitrogen.

The influence of atmospheric deposition of inorganic N-compounds on lake  $\text{NO}_3$  concentrations also can be seen at a more local scale. In Rocky Mountain National Park,  $\text{NO}_3$  concentrations were significantly higher in lakes on the east side of the continental divide than in lakes on the west side (Figure 4a;  $p < 0.01$ ). This pattern probably is due to higher concentrations of inorganic N-compounds in precipitation on the east side of the park, which was noted in a study of snowpack chemistry by Heuer *et al.* (2000). The two sides of the park are separated by the continental divide, and often are affected by different climatic conditions and wind patterns (Baron and Denning, 1993). Storms on the west side of the park come mostly from the relatively unpopulated areas to the west. The east side of the park can be affected by upslope storms that bring pollutants from the urban areas of Denver and Fort Collins, located to the east of the park (Baron and Denning, 1993).

Total inorganic N deposition, which is the sum of wet deposition plus dry deposition, increased from north to south in the Sierra/southern Cascade parks and in the Rocky Mountain parks (Figure 3b, Table III). Wet deposition is the product of inorganic N concentrations in precipitation times precipitation amount, and dry deposition is calculated from ambient air concentrations and deposition velocities (<http://www.epa.gov/acidrain/castnet/methods.html>). Although total inorganic N deposition in the southern Sierra Nevada was highly variable during 1996–1999, it commonly was comparable to total inorganic N deposition in the southern Rocky Mountains (Table III). This similarity in total N deposition is not reflected in  $\text{NO}_3$  concentrations in lakes. The large amounts of precipitation that the Sierra often receive may dilute atmospherically-deposited N in those areas, resulting in lower average  $\text{NO}_3$  concentrations in Sierra/south Cascade lakes compared to those in the Rockies.

It is worth noting that nitrogen deposition estimates to alpine/subalpine basins are poorly constrained, especially at high elevation. Wet deposition is difficult to measure at high-elevation sites because of uncertainties in measuring the water content of snowfall using weighing precipitation gages (Williams *et al.*, 1998). Solute-concentration and wet-deposition maps created by NADP/NTN generally exclude sites at the highest elevations because of stringent criteria for precipitation amount measurements, which seldom are met at high-elevation sites. In most cases,

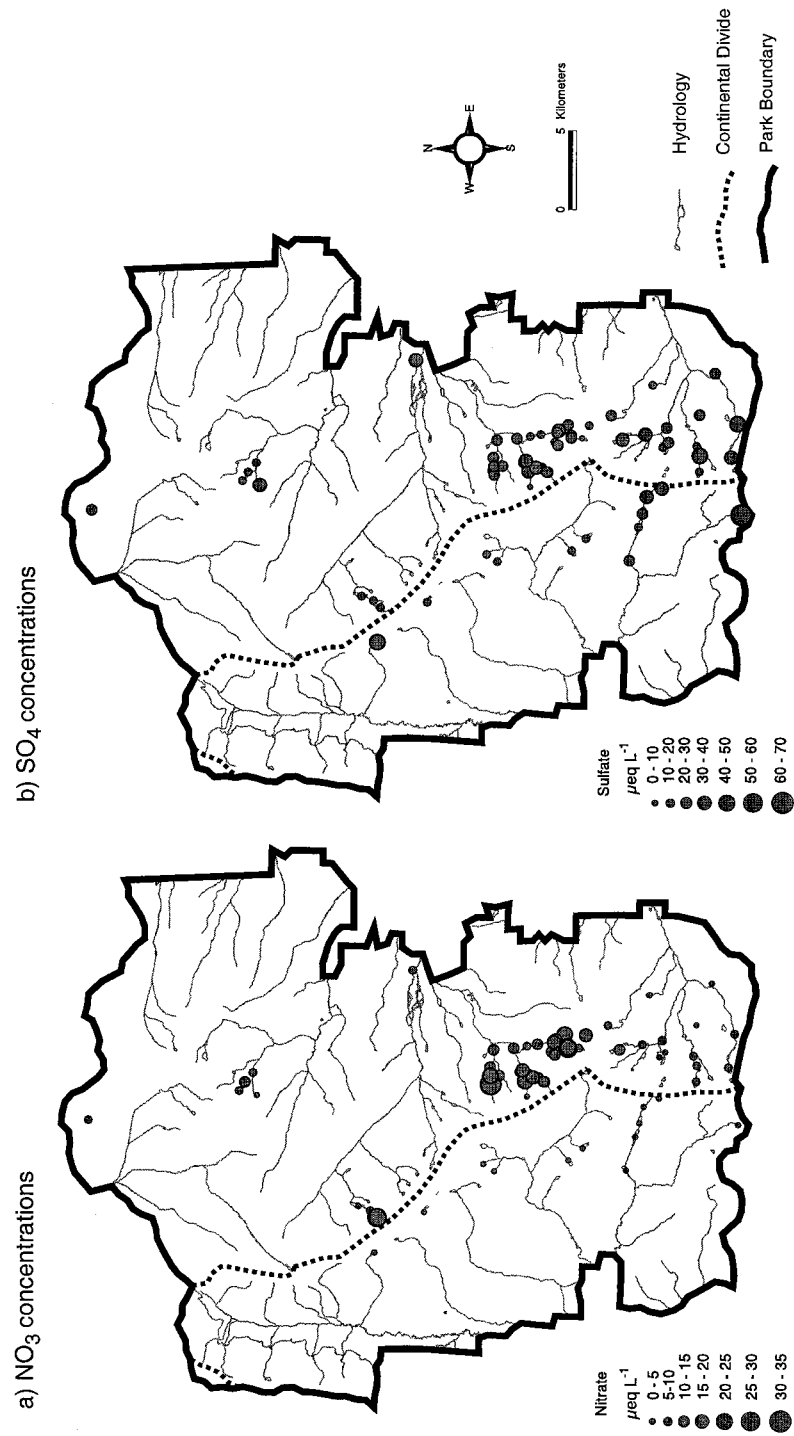


Figure 4. Concentrations of (a)  $\text{NO}_3$ , and (b)  $\text{SO}_4$  in lakes in Rocky Mountain National Park. Data are shown for 22 lakes previously sampled during the 1985 Western Lake Survey, and 26 supplementary lakes. Data pertain to samples collected during fall, 1999.

TABLE III

Estimated dry and wet deposition of inorganic nitrogen (N) and sulphur (S) for 1996–1999 at six national parks in the western United States. Data are not available for Grand Teton National Park. Units are  $\text{kg ha}^{-1}$ . Missing data [m]. Data source: <http://www.epa.gov/acidrain/castnet/>

State	Park	Year	Castnet site ID	Dry deposition		NADP/ NTN site ID	Wet deposition	
				Inorg. N flux	Total S flux		Inorg. N flux	Total S flux
MT	Glacier	1996	GLR468	0.30	0.38	MT05	1.38	2.66
MT	Glacier	1997	GLR468	0.24	0.29	MT05	1.20	2.41
MT	Glacier	1998	GLR468	0.26	0.28	MT05	1.03	2.31
MT	Glacier	1999	GLR468	0.24	0.21	MT05	0.90	1.68
WY	Yellowstone	1996	YEL408	m	m	WY08	0.38	1.03
WY	Yellowstone	1997	YEL408	0.33	0.40	WY08	1.12	1.58
WY	Yellowstone	1998	YEL408	0.31	0.30	WY08	0.67	1.06
WY	Yellowstone	1999	YEL408	0.35	0.35	WY08	0.96	1.30
CO	Rocky Mountain	1996	ROM406	1.47	0.55	CO98	3.42	6.14
CO	Rocky Mountain	1997	ROM406	1.23	0.60	CO98	2.87	5.39
CO	Rocky Mountain	1998	ROM406	1.44	0.67	CO98	2.66	5.14
CO	Rocky Mountain	1999	ROM406	m	m	CO98	3.19	5.20
CA	Lassen Volcanic	1996	LAV410	0.46	0.13	CA96	m	m
CA	Lassen Volcanic	1997	LAV410	0.56	0.15	CA96	m	m
CA	Lassen Volcanic	1998	LAV410	0.56	0.15	CA96	m	m
CA	Lassen Volcanic	1999	LAV410	m	m	CA96	m	m
CA	Yosemite	1996	YOS404	1.07	0.24	CA99	1.41	2.06
CA	Yosemite	1997	YOS404	1.12	0.26	CA99	0.97	0.93
CA	Yosemite	1998	YOS404	0.92	0.25	CA99	4.97	0.93
CA	Yosemite	1999	YOS404	1.07	0.28	CA99	2.29	1.69
CA	Sequoia/Kings	1996	SEK402	m	m	CA75	1.67	1.79
CA	Sequoia/Kings	1997	SEK402	m	m	CA75	1.59	1.19
CA	Sequoia/Kings	1998	SEK402	m	m	CA75	4.28	3.59
CA	Sequoia/Kings	1999	SEK402	2.48	0.70	CA75	2.19	1.62

the maps do not show the relatively high inorganic N wet deposition amounts that occur at the highest elevations, which are due in part to orographically-enhanced precipitation at those sites (Barry, 1973). Dry deposition also is difficult to quantify, and errors have been estimated to be on the order of 50% (Blanchard, 1996).

Differences in climate are another factor that may help explain the lower  $\text{NO}_3$  concentrations in the Sierra/southern Cascade lakes compared to lakes sampled in the Rockies. Summer climate in the Sierra/south Cascades is warmer and drier than in Rockies, and growing seasons tend to be longer (Rundel *et al.*, 1977; Bailey

*et al.*, 1994). The warm air temperatures in the Sierra/south Cascades are reflected in the relatively warm lake temperatures of the lakes measured in this study (Table II). Warm air temperatures and long growing seasons favor assimilation of atmospherically-deposited  $\text{NH}_4$  and  $\text{NO}_3$  by biota, leading to reductions of  $\text{NO}_3$  in surface water. The dry summer climate in the Sierra/south Cascades causes basins there to receive relatively little N in summer rain compared to basins in the Rockies. Summer dry deposition of N in the Sierra/south Cascades is significant (Table III) (Sickman and Melack, in press), but little of the dry-deposited N is transported to surface water until fall, when the rainy season begins. These factors promote low concentrations of  $\text{NO}_3$  in surface water in the Sierra/south Cascades during the summer.

Physical characteristics of catchments determine the ability of ecosystems to assimilate atmospherically-deposited pollutants. Some important physical characteristics include basin topography and the permeability and distribution of soils (and by implication, vegetation). These factors help determine water residence time in the catchment and the degree of interaction between precipitation and catchment soils and vegetation.

A quantitative analysis of basin characteristics is beyond the scope of this paper, but field observations indicate that the Sierra Nevada catchments that were visited tended to have less soil and vegetation than catchments that were visited in the Rocky Mountains (see photos of lake basins at <http://co.water.usgs.gov/projects/CO335/CO335.html>). The observations are supported indirectly by data on basin characteristics reported by Sickman and Melack (in press) in a study of N-cycling in Sierra Nevada and Rocky Mountain catchments. Soil coverage in 15 Sierra Nevada basins averaged 22%, while in 13 Rocky Mountain catchments soil cover averaged 59% (Sickman and Melack, in press). Nitrogen retention averaged 55% in the Sierran basins and 72% in the Rocky Mountain basins (Sickman and Melack, in press). These findings indicate that Sierra Nevada ecosystems have a lower ability to assimilate N-compounds than ecosystems in the Rocky Mountains.

The relatively high  $\text{NO}_3$  concentrations observed in many lakes in the Rocky Mountains, and in a few of the Sierra Nevada lakes, indicate that aquatic ecosystems are being impacted by atmospheric deposition of nitrogen. In pristine ecosystems during the growing season, vegetation consumes most of the available nitrogen, so  $\text{NO}_3$  concentrations in surface waters are quite low. High  $\text{NO}_3$  concentrations in surface waters during the growing season, such as those seen in Rocky Mountain National Park in this study, are indicative of nitrogen saturation (Stoddard, 1994). This disturbance to the ecosystem can lead to shifts in species composition, and in some cases, eutrophication of downstream aquatic ecosystems. It is notable that nitrogen deposition seems to be impacting lakes in Rocky Mountain National Park despite relatively low nitrogen deposition rates of 3 to 5 kg N  $\text{ha}^{-1} \text{yr}^{-1}$  (Campbell *et al.*, 2000) compared to the eastern United States or Europe, where N deposition rates are more than twice as high. Fast hydrologic flushing rates and the scarcity of well-developed soils make high-elevation ecosystems in



the western United States highly sensitive to nitrogen deposition (Williams *et al.*, 1996; Campbell *et al.*, 2000; Sickman and Melack, in press).

## 5.2. SULFATE

The main sources of  $\text{SO}_4$  in the sampled lakes are atmospheric deposition (wet and dry) and mineral weathering (Turk *et al.*, 1993). The importance of these sources appears to differ by region, with both sources being more important in the Rocky Mountains than in the Sierra/south Cascades.

Regional patterns in lake water  $\text{SO}_4$  concentrations (Table II, Figure 2) were similar to regional patterns of  $\text{SO}_4$  in precipitation (Figure 3c), supporting the hypothesis that atmospheric  $\text{SO}_4$  deposition is influencing lake  $\text{SO}_4$  concentrations. The local patterns in lake  $\text{NO}_3$  concentrations in Rocky Mountain National Park (east > west) was less evident for  $\text{SO}_4$  (Figure 4b). This suggests that, in addition to atmospheric sources of  $\text{SO}_4$  from the east, sources to the west also are important.

In the Sierra/south Cascades,  $\text{SO}_4$  concentrations in lake water and in precipitation generally were similar to each other, indicating that atmospheric deposition probably was the dominant source of  $\text{SO}_4$  in those lakes. In the Rocky Mountains, median concentrations of  $\text{SO}_4$  in lake water in each of the parks were approximately twice as high as  $\text{SO}_4$  concentrations in local precipitation. In addition to atmospheric deposition inputs, other factors that were considered that could affect lake  $\text{SO}_4$  concentrations in the Rocky Mountains include evapotranspiration, dry deposition, mineral weathering, and the release of sulfur stored in catchment soils.

It is doubtful that evapotranspiration would affect Rocky Mountain lakes more than Sierra/south Cascade lakes because summer climate is cooler and wetter in the Rocky Mountains than in the Sierra/south Cascades. Dry deposition of  $\text{SO}_4$  appears comparable in the Sierra/south Cascades and in the Rocky Mountains (Table III), and is a small component of total sulfur deposition.

Mineral weathering may provide an additional source of  $\text{SO}_4$  for a few lakes in the Rocky Mountains, but was estimated to account for less than 25% of atmospherically-deposited sulfur at most lakes sampled during the Western Lake Survey (Turk and Spahr, 1991). Mineral weathering fluxes of S were calculated for Loch Vale, a basin in Rocky Mountain National Park, by multiplying annual mass of rock weathered times the S concentration measured in three rock samples. Mass of rock weathered was calculated from solute mass balance (Mast *et al.*, 1990), accounting for differential weathering among minerals. If the rock samples were representative of the basin lithology, mineral weathering sources of S could account for less than  $0.4 \text{ kg ha}^{-1} \text{ yr}^{-1}$ , which is less than 7% of annual S deposition in Loch Vale (Table III).

Release of atmospherically-derived sulfur stored in catchment soils might account for some of the lake  $\text{SO}_4$  measured in the current study, but  $\text{SO}_4$  adsorption capacities of soils in Rocky Mountain National Park are very low (Baron *et al.*, 1992). Trend analyses on NADP/NTN data indicate that  $\text{SO}_4$  concentrations in

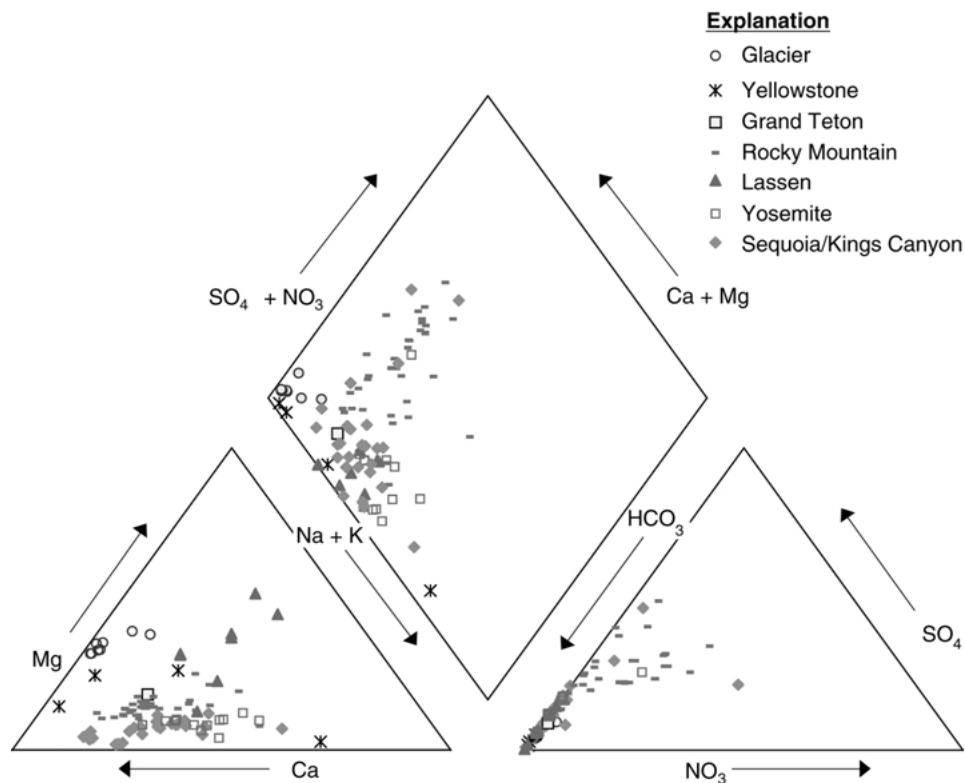


Figure 5. Piper diagram showing relative concentrations of cations and anions in lakes in seven national parks in the western United States.

precipitation declined at most sites in the western United States between 1985–1999. Atmospherically-derived sulfur that is temporarily retained in catchment soils would be released slowly over time, providing a transient source of  $\text{SO}_4$  to surface water. To summarize, higher wet deposition of S is the most likely reason for higher  $\text{SO}_4$  concentrations in lakes in the Rocky Mountains than in the Sierra/south Cascades.

### 5.3. WEATHERING PRODUCTS: BASE CATIONS, ALKALINITY

Mineral weathering contributes the majority of base cations and alkalinity to alpine/subalpine lakes in the Rockies and Sierra/south Cascades. Solute mass-balance estimates for nine basins in Rocky Mountain National Park indicate that wet deposition contributes 15–20% of cation loads in streams (Sueker *et al.*, 2001). Mass-balance estimates for the Emerald Lake basin, in Sequoia/Kings Canyon National Park, indicate that wet deposition contributes 15–30% of base cations in streams there (Williams and Melack, 1991). Dry deposition is likely to be of comparable or smaller magnitude than wet deposition.

Variations in base cation and alkalinity concentrations among the parks largely reflect differences in the dominant mineral weathering reactions in each park (Figure 5). In Glacier National Park, carbonate minerals are abundant in the sedimentary rocks underlying most of the park (Whipple, 1992). The influence of carbonate mineral weathering is evidenced by high concentrations of Ca, Mg, and alkalinity in surface water (Table II), high (Ca + Mg):total cation ratios (left triangle of Figure 5), high cation:silica ratios (Table II), and a strong correlation between (Ca + Mg) and alkalinity ( $r^2 = 0.97$ , slope = 0.95).

In Yellowstone National Park, volcanic rocks predominate (U.S. Geological Survey, 1972), but hydrothermal solutions strongly accelerate weathering reactions locally. As a result, lake chemistry tends to be highly variable in Yellowstone, as can be seen for cations in the left triangle of Figure 5.

Bedrock in Rocky Mountain National Park is mostly granitic gneiss (Braddock and Cole, 1990), which tends to weather relatively slowly, but it contains trace amounts of calcite in some areas (Mast *et al.*, 1990). As a result, surface water in Rocky Mountain National Park has higher Ca concentrations than would be expected based on weathering of the dominant minerals present in the bedrock (quartz, feldspar, and biotite). Another interesting feature of samples from Rocky Mountain National Park is the importance of  $\text{NO}_3$  and  $\text{SO}_4$  among anions compared to samples from other parks (see right triangle of Figure 5). This suggests that strong acid weathering, due to inputs of acidifying N and S compounds from the atmosphere, is more important in Rocky Mountain National Park than in other parks in the study.

In Yosemite and Sequoia/Kings Canyon National Parks, bedrock is mostly granite and granodiorite, which predominantly contains quartz and feldspar (Ross, 1958; Bateman, 1992). These minerals weather relatively slowly, leading to low concentrations of base cations and alkalinity in the lakes in those parks. A high (Na + K):total cation ratio for samples from Yosemite indicates that Na and K feldspar weathering is more important and carbonate weathering is less important than in most of the other parks (see left triangle of Figure 5).

In Lassen Volcanic National Park, bedrock is dacite and the main minerals are quartz, feldspar, and biotite (Diller, 1894). Although dacite tends to weather more rapidly than granite or granodiorite, soils are very young, thin, and poorly developed. Because of this, and because of relatively short flowpaths in the small drainage basins that are common in the park, concentrations of base cations and alkalinity in lakes in Lassen Volcanic National Park are quite low (Table II). Magnesium is relatively important in samples from Lassen Volcanic National Park, suggesting that weathering of Mg-rich mica (biotite) is important there.

## 6. Comparisons with Other Recent Lake Surveys

In Rocky Mountain National Park, in addition to the set of 22 WLS lakes that were resampled, a supplementary set of 26 lakes and 18 streams were sampled as part of a related study. The supplementary lakes and stream samples permit a more thorough characterization of surface-water chemistry in Rocky Mountain National Park. Concentrations of most constituents were similar in the set of WLS lakes and in the larger set of Rocky Mountain National Park surface waters (WLS lakes plus supplementary lakes and streams), with the exception of alkalinity and  $\text{NO}_3$  (Table II, Table IV).

Alkalinity was substantially lower and  $\text{NO}_3$  was much higher in the larger set of surface waters than in the set of WLS lakes. These differences in chemistry probably reflect differences in basin characteristics; many of the additional lakes and streams that were sampled were at relatively high elevation in small cirque basins with abundant talus and steeply-sloping topography. In a previous study relating stream chemistry to basin characteristics in Rocky Mountain National Park, it was established that basin slope and young surficial debris (mostly talus) were negatively correlated with alkalinity and positively correlated with  $\text{NO}_3$  concentrations in streams (Clow and Sueker, 2000). These relations were interpreted to result largely from a lack of neutralization and nitrogen uptake capacity in talus environments due to fast flow rates and a paucity of well-developed soil (Clow and Sueker, 2000). Nitrification processes in talus also may play a role.

Recent synoptic survey data for alpine/subalpine areas is rare. Although 14 yr older, the 1985 Western Lake Survey data set is the most directly comparable data set to the present study. A detailed comparison of data from the two studies is provided in Clow *et al.* (in review).

A survey of mountain and forest lake chemistry was conducted in Norway during the fall of 1995 (Skjelvåle and Wright, 1998). Concentrations of  $\text{Ca} + \text{Mg}$  in the Norwegian mountain lakes were relatively low compared to lakes in most of the parks in this study, except Yosemite and Lassen Volcanic National Parks (Tables II and V). Concentrations of  $\text{SO}_4$  and  $\text{NO}_3$  in the Norwegian mountain lakes were comparable to those measured in lakes in the Rocky Mountain parks, and were higher than those measured in lakes in the Sierra/south Cascade parks. The combination of moderately high  $\text{SO}_4$  and  $\text{NO}_3$ , coupled with low base cation concentrations result in low alkalinity in the Norwegian mountain lakes, and may provide an indication of how surface-water chemistry in the Sierra/south Cascades might be impacted if  $\text{SO}_4$  and  $\text{NO}_3$  deposition were to increase there.

## 7. Recommendations for Future Studies

Lake selection in this study was based primarily on the desire to repeat the portion of the 1985 Western Lake Survey that was done in national parks in the western

TABLE IV  
Summary statistics for 22 WLS lakes, 26 additional lakes, and 18 streams sampled in Rocky Mountain National Park during fall, 1999

	Temp.	SC	pH	Alkalinity	Ca	Mg	Na	K	NH <sub>4</sub>	H <sub>4</sub> SiO <sub>4</sub>	Cl	SO <sub>4</sub>	NO <sub>4</sub>	DOC	UVA	
n = 66	Mean	6.5	11.6	6.7	55.5	62.3	15.1	22.6	3.3	≤0.5	33.0	2.4	24.4	10.4	1.3	0.167
	Minimum	1.0	5.0	5.9	7.4	16.9	3.2	6.3	1.1	≤0.5	2.5	1.1	7.9	≤0.3	≤0.3	0.014
	Median	7.0	11.5	6.7	49.6	59.8	13.9	19.9	3.0	≤0.5	30.5	2.2	22.4	9.2	1.1	0.016
	Maximum	12.0	23.0	7.2	170.6	140.2	46.9	97.3	8.4	3.9	152.6	9.2	65.9	32.9	7.0	0.010

Temperature (Temp.) is in °C; DOC is in mg L<sup>-1</sup>, specific conductance (SC) is in μS cm<sup>-1</sup>; all other units except pH are μeq L<sup>-1</sup>. DOC refers to dissolved organic carbon. UVA refers to ultra-violet absorbance.

TABLE V

Median concentrations for lakes in Norway during fall, 1995. Units are  $\mu\text{eq L}^{-1}$

	Count	Alkalinity	Ca + Mg <sup>b</sup>	SO <sub>4</sub> <sup>b</sup>	NO <sub>3</sub>
Mountains <sup>a</sup>	350	16	30	26	1.6
Forest <sup>a</sup>	363	69	93	47	2.0

<sup>a</sup> Skjelvale and Wright, 1998.

<sup>b</sup> Corrected for sea-salt inputs.

United States (Clow *et al.*, in review). In the original Western Lake Survey, lakes were selected using a stratified random approach, which permitted extrapolation from the sample of lakes ( $n = 719$ ) to the target population of lakes ( $n = 10\,393$ ). Extrapolation from the sample of lakes in this study ( $n = 69$ ) to a target population is not possible because lake selection was not probability based, and using a subset of the WLS lakes might have created a biased sample. Future lake surveys in national parks should consider using a stratified random approach for selecting lakes within each park. Strata could be defined using basin characteristics, which can be quantified using a Geographic Information System (GIS) approach. Careful consideration also should be given to the number of lakes required to adequately characterize water chemistry in a given park. One deficiency of the present study was the lack of sufficient samples in Grand Teton National Park.

This study focused on the low-flow period in the fall, when seasonal variations in lake chemistry typically are minimal. Aquatic ecosystems in alpine/subalpine areas commonly undergo substantial declines in alkalinity and pH during snow-melt, when water residence times are relatively short (Williams *et al.*, 1993; Campbell *et al.*, 1995). Monitoring programs in the parks may wish to consider including intensive lake or stream monitoring at a few sites in each park so that seasonal variations in surface-water chemistry can be evaluated in basins with a range of physical and biologic characteristics.

## 8. Conclusions

Sixty nine lakes in seven national parks in the western United States that were previously sampled during the 1985 Western Lake Survey were resampled during the fall of 1999. Lakes in the Sierra/southern Cascades (Lassen Volcanic, Yosemite, Sequoia/Kings Canyon National Parks) and in the southern Rocky Mountains (Rocky Mountain National Park) were very dilute; median specific conductances ranged from 4.4 to 12.2  $\mu\text{S cm}^{-1}$  and median alkalinities ranged from 32.2 to 72.9  $\mu\text{eq L}^{-1}$ . Specific conductances and alkalinity concentrations were substantially higher in lakes in the central and northern Rocky Mountains (Grand Teton, Yellowstone,

and Glacier National Parks), probably due to the prevalence of more reactive bedrock types.

The low specific conductances and alkalinity concentrations in lakes in the Sierra/southern Cascades and southern Rocky Mountain parks indicate that aquatic and terrestrial ecosystems in those parks have little ability to neutralize acidic deposition. This is because of a paucity of vegetation and of well-developed soils, and because of the prevalence of relatively resistant bedrock types. These factors, combined with fast flushing rates through soils, make aquatic ecosystems in these parks vulnerable to the effects of atmospherically-deposited pollutants, especially during snowmelt.

Atmospheric deposition of N compounds and  $\text{SO}_4$  appear to have a significant influence on lake chemistry in national parks in the western United States. This influence clearly is more pronounced in the parks in the Rocky Mountains than in the parks in the Sierra/southern Cascades, as indicated by the higher  $\text{NO}_3$  and  $\text{SO}_4$  concentrations in the lakes in the Rocky Mountains. Elevated  $\text{NO}_3$  concentrations in lakes in Rocky Mountain National Park support the hypothesis that some park ecosystems may be in the early stages of nitrogen saturation.

Long-term monitoring programs are needed in the parks to allow periodic evaluation of the health of aquatic and terrestrial ecosystems. Surface water surveys should carefully consider the design of water-quality monitoring programs to ensure that extrapolations can be made from sampled lakes to a larger target population of lakes. A stratified random approach, such as that used during the original Western Lake Survey, should be considered for selecting monitoring sites in each park. Intensive monitoring throughout the year at a few sites in each park would provide critical information on how surface-water chemistry varies seasonally; this information is especially important for the snowmelt period, when aquatic ecosystems in alpine/subalpine areas are most stressed.

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